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[40124/02501]

IN THE UNITED STATES PATENT AND TRADEMARK OFFICE

Inventor(s)	:	**Lutz MAY**
Serial No.	:	**To Be Assigned**
Filing Date	:	**December 30, 2003**
For	:	**PCM-ENCODED TORQUE SENSING TECHNOLOGY**

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PROVISIONAL PATENT APPLICATION TRANSMITTAL

SIRS:

This is a request for filing a PROVISIONAL APPLICATION FOR PATENT under 37 CFR 1.53(c).

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1. **38** sheets of Specification and
2. Return postcard.

Please charge the Deposit Account of **Fay Kaplun & Marcin, LLP, No. 50-1492** in the amount of **$160.00** for the filing fee.

The Commissioner is hereby authorized to charge the payment of any additional fees associated with this communication or arising during the pendency of this application, to the Deposit Account of **Fay Kaplun & Marcin, LLP No. 50-1492.**

Date: December 30, 2003

By: ______________________
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US Provisional Patent Application

PCM-Encoded Torque Sensing Technology

Field of the Invention

The magnetic principle based mechanical-stress sensing technology allows to design and to produce a wide range of "physical-parameter-sensors" (like Force Sensing, Torque Sensing, and Material Diagnostic Analysis) that can be applied where Ferro-Magnetic materials are used. The most common technologies used to build "magnetic-principle-based" sensors are: Inductive differential displacement measurement (requires torsion shaft), Measuring the changes of the materials permeability, and measuring the magnetostriction effects.

Over the last 20 years a number of different companies have developed their own and very specific solution in how to design and how to produce a magnetic principle based torque sensor (i.e. ABB, FAST, Frauenhofer Institute, FT, Kubota, MDI, NCTE, RM, Siemens, and others). These technologies are at various development stages and differ in "how-it-works", the achievable performance, the systems reliability, and the manufacturing / system cost.

Some of these technologies require that mechanical changes are made to the shaft where torque should be measured (chevrons), or rely on the mechanical torsion effect (require a long shaft that twists under torque), or that something will be attached to the shaft itself (press-fitting a ring of certain properties to the shaft surface,), or coating of the shaft surface with a special substance. No-one has yet mastered a high-volume manufacturing process that can be applied to (almost) any shaft size, achieving tight performance tolerances, and is not based on already existing technology patents.

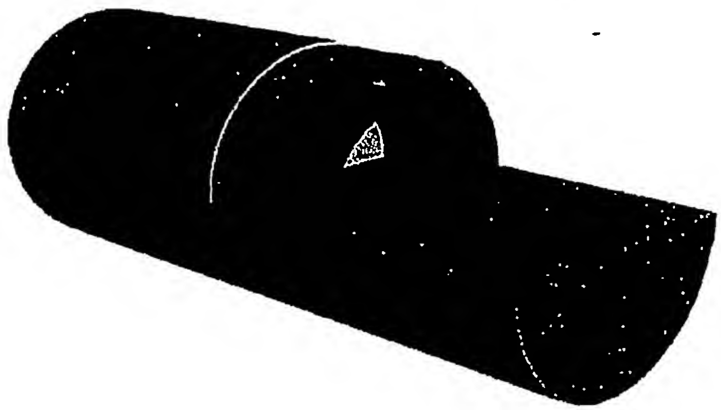
Summary of the Invention and Exemplary embodiments of the present invention

In the following, exemplary embodiments of the present invention relating to a magnetostriction principle based ***Non-Contact-Torque*** (NCT) Sensing Technology are described that offer to the user a whole host of new features and improved performances, previously not available. This technology enables the realization of a fully-integrated (small in space), real-time (high signal bandwidth) torque measurement, which is reliable and can be produced at an affordable cost, at any desired quantities. This technology is called: ***PCME*** (for Pulse-Current-Modulated Encoding) or Magnetostriction Transversal Torque Sensor.

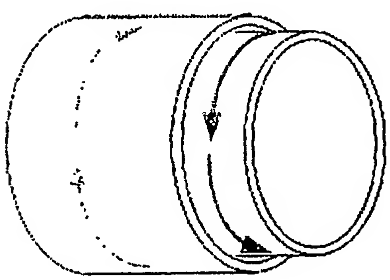
The PCME technology can be applied to the shaft without making any mechanical changes to the shaft, or without attaching anything to the shaft. Most important, the PCME technology can be applied to any shaft diameter (most other technologies have here a limitation) and does not need to rotate / spin the shaft during the encoding process (very simple and low-cost manufacturing process) which makes this technology very applicable for high-volume application.

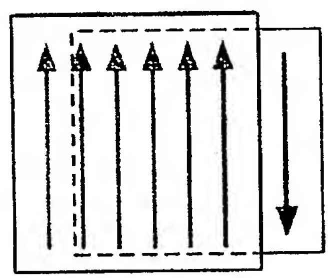
Magnetic Field Structure (Sensor Principle)

The sensor life-time depends on a "closed-loop" magnetic field design. The PCME technology is based on two magnetic field structures, stored above each other, and running in opposite directions. When no torque stress is applied to the shaft (also called Sensor Host, or SH) then the SH will act magnetically neutral (no magnetic field can be sensed at the outside of the SH).



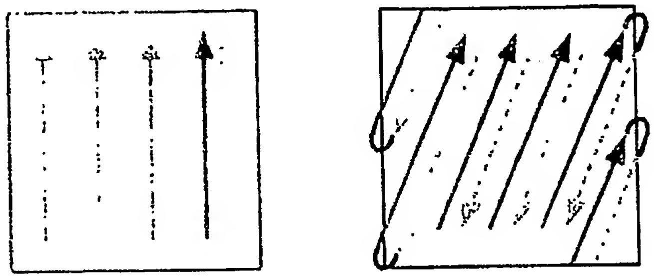
Picture: The picture shows an exemplary embodiment of the present invention where two magnetic fields are stored in the SH and running in endless circles. The outer field runs in one direction, while the inner field runs in the opposite direction.





Drawing: The PCME sensing technology uses two Counter-Circular magnetic fiel d loops that are stored on top of each other (Picky-Back mode).

When mechanical stress (like torque) is applied at both ends of the PCME magnetized SH (Sensor Host, or Shaft) then the magnetic flux lines of both magnetic structures (or loops) will tilt in proportion to the applied torque.

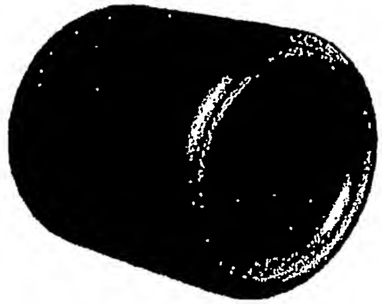


Drawing: When no mechanical stresses are applied to the SH the magnetic flux lines are running in its original path. When mechanical tresses are applied the magnetic flux lines tilt in proportion to the applied stress (like torque).

Depending on the applied torque direction (clockwise or anti-clockwise, in relation to the SH) the magnetic flux lines will either tilt to the right or tilt to the left. Where the magnetic flux lines reach the boundary of the magnetically encoded region, the magnetic flux lines from the upper layer will join-up with the magnetic flux lines from the lower layer and visa-versa. This will then form a perfectly controlled toroidal shape.

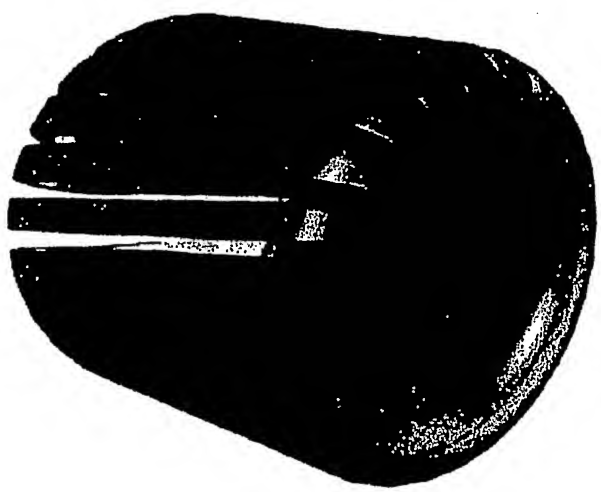
The benefits of such a magnetic structure are:

- ☐ Reduced (almost eliminated) parasitic magnetic field structures when mechanical stress is applied to the SH (this will result in better RSU performances).
- ☐ Higher Sensor-Output Signal-Slope as there are two "active" layers that compliment each other when generating a mechanical stress related signal. Explanation: When using a single-layer sensor design, the "tilted" magnetic flux lines that exit at the encoding region boundary have to create a "return passage" from one boundary side to the other. This effort effects how much signal is available to be sensed and measured outside of the SH with the secondary sensor unit.
- ☐ There are almost no limitations on the SH (shaft) dimensions where the PCME technology will be applied to. The dual layered magnetic field structure can be adapted to any solid or hollow shaft dimensions.
- ☐ The physical dimensions and sensor performances are in a very wide range programmable and therefore can be tailored to the targeted application.
- ☐ This sensor design allows to measure mechanical stresses coming from all three dimensions axis, including in-line forces applied to the shaft (applicable as a load-cell). Explanation: Earlier magnetostriction sensor designs (for example from FAST Technology) have been limited to be sensitive in 2 dimensional axis only, and could not measure in-line forces.



Picture: When torque is applied to the SH, the magnetic flux lines from both Counter-Circular magnetic loops are connecting to each other at the sensor region boundaries.

When mechanical torque stress is applied to the SH then the magnetic field will no longer run around in circles but tilt slightly in proportion to the applied torque stress. This will cause the magnetic field lines from one layer to connect to the magnetic field lines in the other layer, and with this form a toroidal shape.



Picture: An exaggerated presentation of how the magnetic flux line will form an angled toroidal structure when high levels of torque are applied to the SH.

Features and Benefits of the PCM-Encoding (PCME) Process

The magnetostriction NCT sensing technology from NCTE according to the present invention offers high performance torque sensing features like:

- ☐ No mechanical changes required on the Sensor Host (already existing shafts can be used as they are)
- ☐ Nothing will be attached to the Sensor Host (therefore nothing can fall off or change over the shaft-lifetime = high MTBF)
- ☐ During measurement the SH can rotate at any desired speed (no limitations on rpm)
- ☐ Very good RSU (Rotational Signal Uniformity) performances
- ☐ Excellent measurement linearity (up to 0.01% of FS)
- ☐ High measurement repeatability
- ☐ Very high signal resolution (better than 14 bit)
- ☐ Very high signal bandwidth (better than 10 kHz)

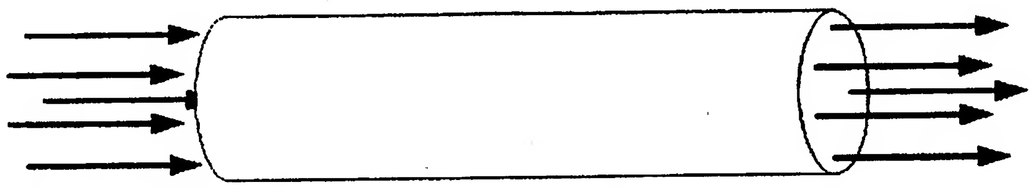
Depending on the chosen type of magnetostriction sensing technology, and the chosen physical sensor design, the mechanical power transmitting shaft (also called "Sensor Host" or in short "SH") can be used "as is" without making any mechanical changes to it or without attaching anything to the shaft. This is then called a "true" Non-Contact-Torque measurement principle allowing the shaft to rotate freely at any desired speed in both directions.

The here described PCM-Encoding (PCME) manufacturing process according to an exemplary embodiment of the present invention provides additional features no other magnetostriction technology can offer (*Uniqueness of this technology*):

- ☐ More then three times signal strength in comparison to alternative magnetostriction encoding processes (like the "RS" process from FAST).
- ☐ Easy and simple shaft loading process (high manufacturing through-putt).
- ☐ No moving components during magnetic encoding process (low complexity manufacturing equipment = high MTBF, and lower cost).
- ☐ Process allows NCT sensor to be "fine-tuning" to achieve target accuracy of a fraction of one percent.
- ☐ Manufacturing process allows shaft "pre-processing" and "post-processing" in the same process cycle (high manufacturing through-putt).
- ☐ Sensing technology and manufacturing process is ratio-metric and therefore is applicable to all shaft or tube diameters.
- ☐ The PCM-Encoding process can be applied while the SH is already assembled (depending on accessibility) (maintenance friendly).
- ☐ Final sensor is insensitive to axial shaft movements (the actual allowable axial shaft movement depends on the physical "length" of the magnetically encoded region).
- ☐ Magnetically encoded SH remains neutral and has little to non magnetic field when no forces (like torque) are applied to the SH.
- ☐ Sensitive to mechanical forces in all three dimensional axis.

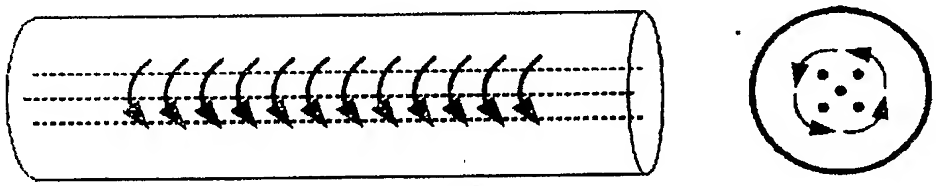
Magnetic Flux Distribution in the SH

The PCME processing technology is based on using electrical currents, passing through the SH (Sensor Host or Shaft) to achieve the desired, permanent magnetic encoding of the Ferro-magnetic material. To achieve the desired sensor performance and features a very specific and well controlled electrical current is required. Early experiments that used DC currents failed because of luck of understanding how small amounts and large amounts of DC electric current are traveling through a conductor (in this case the "conductor" is the mechanical power transmitting shaft, also called Sensor Host or in short "SH").



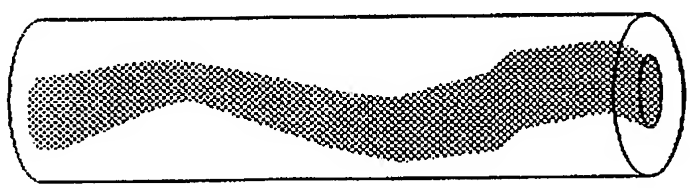
Drawing: Assumed electrical current density in a conductor

It is widely assumed that the electric current density in a conductor is evenly distributed over the entire cross-section of the conductor when an electric current (DC) passes through the conductor.



Drawing: Small electrical current forming magnetic field that ties current path in a conductor.

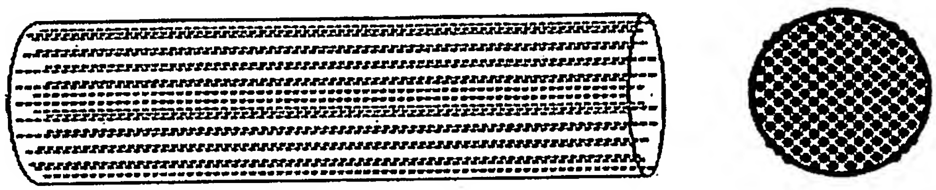
It is our experience that when a small amount of electrical current (DC) is passing through the conductor that the current density is highest at the center of the conductor. The two main reasons for this are: The electric current passing through a conductor generates a magnetic field that is tying together the current path in the center of the conductor, and the impedance is the lowest in the center of the conductor.



Drawing: Typical flow of small electrical currents in a conductor

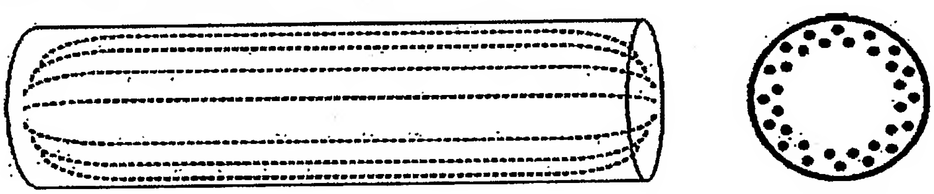
In reality, however, the electric current may not flow in a "straight" line from one connection pole to the other (similar to the shape of electric lightening in the sky).

At a certain level of electric current the generated magnetic field is large enough to cause a permanent magnetization of the Ferro-magnetic shaft material. As the electric current is flowing near or at the center of the SH, the permanently stored magnetic field will reside at the same location: near or at the center of the SH. When now applying mechanical torque to the shaft then shaft internally stored magnetic field will respond by tilting its magnetic flux path in accordance to the applied mechanical force. As the permanently stored magnetic field lies deep below the shaft surface the measurable effects are very small, not uniform and therefore not sufficient to build a reliable NCT sensor system.



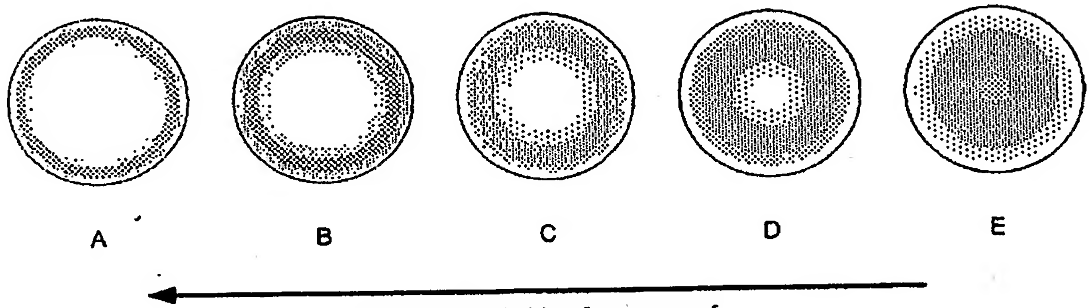
Drawing: Uniform current density in a conductor at saturation level.

Only at the saturation level is the electric current density (when applying DC) evenly distributed at the entire cross section of the conductor. The amount of electrical current to achieve this saturation level is extremely high and is mainly influenced by the cross section and conductivity (impedance) of the used conductor.



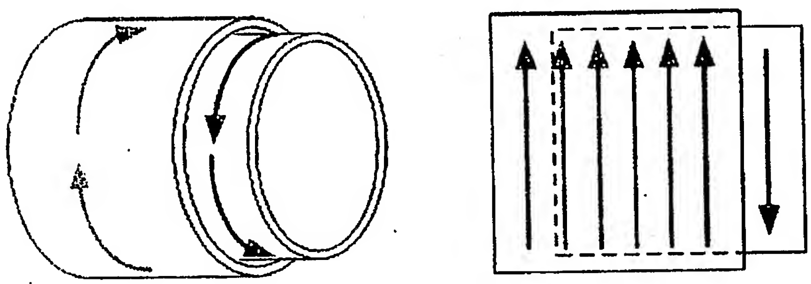
Drawing: Electric current traveling beneath or at the surface of the conductor (Skin-Effect).

It is also widely assumed that when passing through alternating current (like a radio frequency signal) through a conductor that the signal is passing through the skin layers of the conductor, called the Skin Effect. The chosen frequency of the alternating current defines the "Location / position" and "depth" of the Skin Effect. At high frequencies the electrical current will travel right at or near the surface of the conductor (A) while at lower frequencies (in the 5 to 10 Hz regions for a 20 mm diameter SH) the electrical alternating current will penetrate more the center of the shafts cross section (E). Also, the relative current density is higher in the current occupied regions at higher AC frequencies in comparison to the relative current density near the center of the shaft at very low AC frequencies (as there is more space available for the current to flow through).



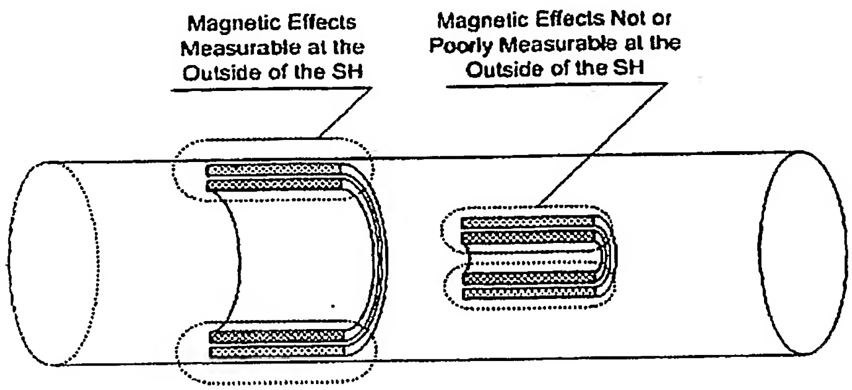
Drawing: The electrical current density of an electrical conductor (cross-section 90 deg to the current flow) when passing through the conductor an alternating current at different frequencies.

The desired magnetic field design of the PCME sensor technology are two circular magnetic field structures, stored in two layers on top of each other ("Picky-Back"), and running in opposite direction to each other (Counter-Circular).



Drawing: Desired magnetic sensor structure: two endless magnetic loops placed on top of each other, running in opposite directions to each other: Counter-Circular "Picky-Back" Field Design.

To make this magnetic field design highly sensitive to mechanical stresses that will be applied to the SH (shaft), and to generate the largest sensor signal possible, the desired magnetic field structure has to be placed nearest to the shaft surface. Placing the circular magnetic fields to close to the center of the SH will cause damping of the user available sensor-output-signal slope (most of the sensor signal will travel through the Ferro-magnetic shaft material as it has a much higher permeability in comparison to air), and increases the non-uniformity of the sensor signal (in relation to shaft rotation and to axial movements of the shaft in relation to the secondary sensor.



Drawing: Magnetic field structures stored near the shaft surface and stored near the center of the shaft.

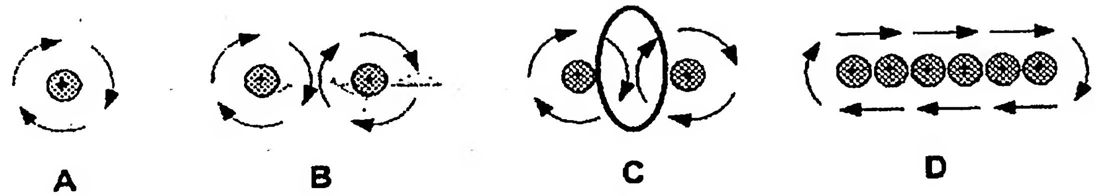
It may be difficult to achieve the desired permanent magnetic encoding of the SH when using AC (alternating current) as the polarity of the created magnetic field is constantly changing and therefore may act more as a Degaussing system. .

The PCME technology requires that a strong electrical current ("uni-polar" or DC, to prevent erasing of the desired magnetic field structure) is traveling right below the shaft surface (to ensure that the sensor signal will be uniform and measurable at the outside of the shaft). In addition a Counter-Circular, "picky back" magnetic field structure needs to be formed.

It is possible to place the two Counter-Circular magnetic field structures in the shaft by storing them into the shaft one after each other. First the inner layer will be stored in the SH, and then the outer layer by using a weaker magnetic force (preventing that the inner layer will be neutralized and deleted by accident. To achieve this, the known "permanent" magnet encoding techniques can be applied as described in patents from FAST technology, or by using a combination of electrical current encoding and the "permanent" magnet encoding.

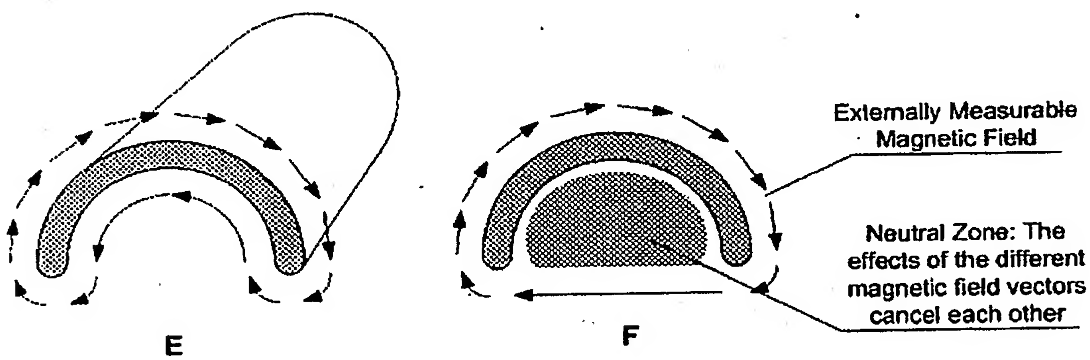
A much simpler and faster encoding process uses "only" electric current to achieve the desired Counter-Circular "Picky-Back" magnetic field structure. The most challenging part here is to generate the Counter-Circular magnetic field.

A uniform electrical current will produce a uniform magnetic field, running around the electrical conductor in a 90 deg angle, in relation to the current direction (A). When placing two conductors side-by-side (B) then the magnetic field between the two conductors seems to cancel-out the effect of each other (C). Although still present, there is no detectable (or measurable) magnetic field between the closely placed two conductors. When placing a number of electrical conductors side-by-side (D) the "measurable" magnetic field seems to go around the outside the surface of the "flat" shaped conductor.



Drawing: The magnetic effects when looking at the cross-section of a conductor with a uniform current flowing through them.

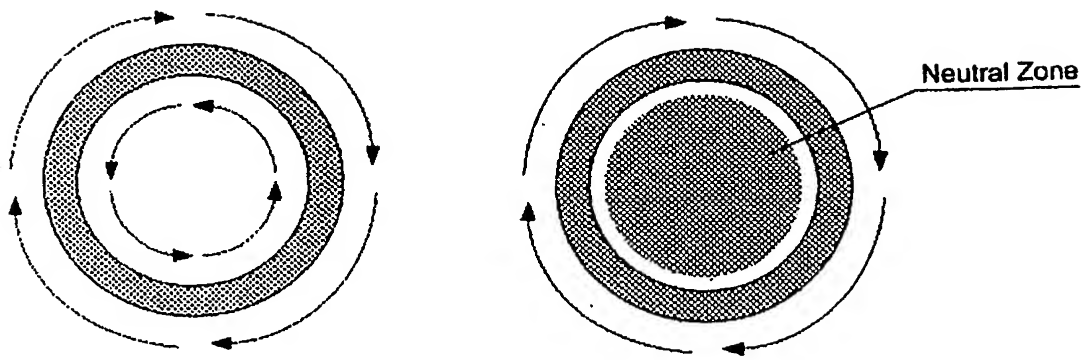
The "flat" or rectangle shaped conductor has now been bent into a "U"-shape. When passing an electrical current through the "U"-shaped conductor then the magnetic field following the outer dimensions of the "U"-shape is canceling out the measurable effects in the inner halve of the "U".



Drawing: The zone inside the "U"-shaped conductor seem to be magnetically "Neutral" when an electrical current is flowing through the conductor.

When no mechanical stress is applied to the cross-section of a "U"-shaped conductor it seems that there is no magnetic field present inside of the "U" (F). But when bending or twisting the "U"-shaped conductor the magnetic field will no longer follow its original path (90 deg angle to the current flow). Depending on the applied mechanical forces, the magnetic field begins to change slightly its path. At that time the magnetic-field-vector that is caused by the mechanical stress can be sensed and measured at the surface of the conductor, inside and outside of the "U"-shape. Note: This phenomena is applies only at very specific electrical current levels.

The same applies to the "O"-shaped conductor design. When passing a uniform electrical current through an "O"-shaped conductor (Tube) the measurable magnetic effects inside of the "O" (Tube) have canceled-out each other (G).



G H

Drawing: The zone inside the "O"-shaped conductor seem to be magnetically "Neutral" when an electrical current is flowing through the conductor.

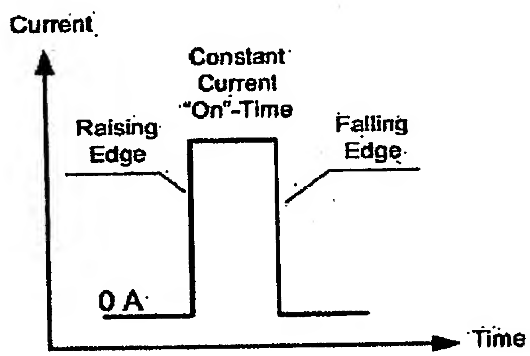
However, when mechanical stresses are applied to the "O"-shaped conductor (Tube) it becomes evident that there has been a magnetic field present at the inner side of the "O"-shaped conductor. The inner, counter directional magnetic field (as well as the outer magnetic field) begins to tilt in relation to the applied torque stresses. This tilting field can be clearly sensed and measured.

Encoding Pulse Design

To achieve the desired magnetic field structure (Counter-Circular, Picky-Back, Fields Design) inside the SH, according to an exemplary embodiment of a method of the present invention, unipolar electrical current pulses are passed through the Shaft (or SH). By using "pulses" the desired "Skin-Effect" can be achieved. By using a "unipolar" current direction (not changing the direction of the electrical current) the generated magnetic effect will not be erased accidentally.

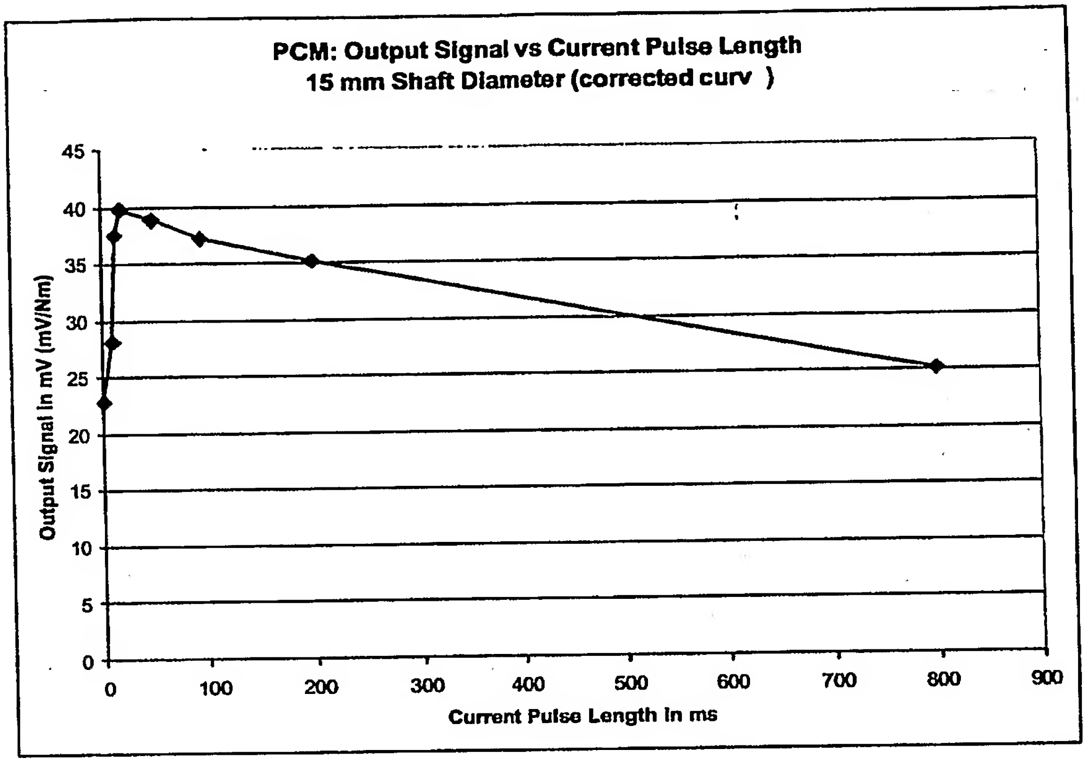
The used current pulse shape is most critical to achieve the desired PCME sensor design. Each parameter has to be accurately and repeatable controlled: Current raising time, Constant current on-time, Maximal current amplitude, and Current falling time. In addition it is very critical that the current enters and exits very uniformly around the entire shaft surface.

Rectangle Current Pulse Shape



Graph: Rectangle shaped electrical current pulse

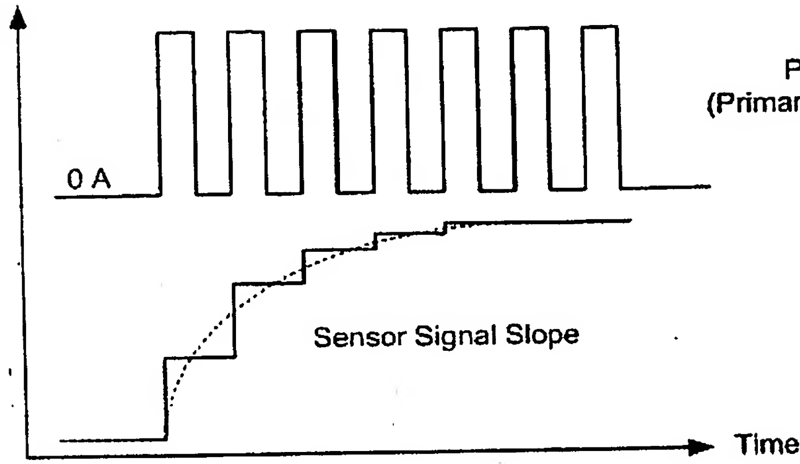
A rectangle shaped current pulse has a fast raising positive edge and a fast falling current edge. When passing a rectangle shaped current pulse through the SH, the raising edge is responsible for forming the targeted magnetic structure of the PCME sensor while the flat "on" time and the falling edge of the rectangle shaped current pulse are counter productive.



Graph: Relationship between rectangles shaped Current Encoding Pulse-Width (Constant Current On-Time) and Sensor Output Signal Slope.

In the following example a rectangle shaped current pulse has been used to generate and store the Couter-Circilar "Picky-Back" field in a 15 mm diameter, 14CrNi14 shaft. The pulsed electric current had its maximum at around 270 Ampere. The pulse "on-time" has been electronically controlled. Because of the high frequency component in the rising and falling edge of the encoding pulse, this experiment can not truly represent the effects of a true DC encoding SH. Therefore the Sensor-Output-Signal Slope-curve eventually flattens-out at above 20 mV/Nm when passing the Constant-Current On-Time of 1000 ms.

Without using a fast raising current-pulse edge (like using a controlled ramping slope) the sensor output signal slope would have been very poor (below 10 mV/Nm). Note: In this experiment (using 14CrNi14) the signal hysteresis was around 0.95% of the FS signal (FS = 75 Nm torque).

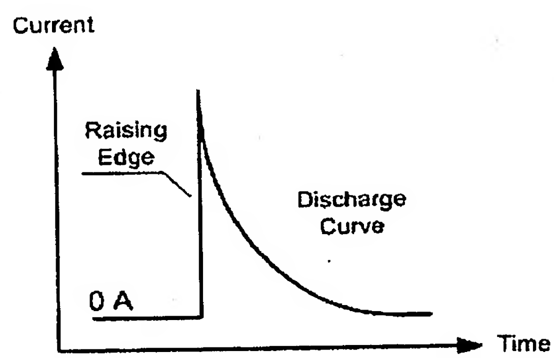


Graph: Increasing the Sensor-Output Signal-Slope by using several rectangle shaped current pulses in succession.

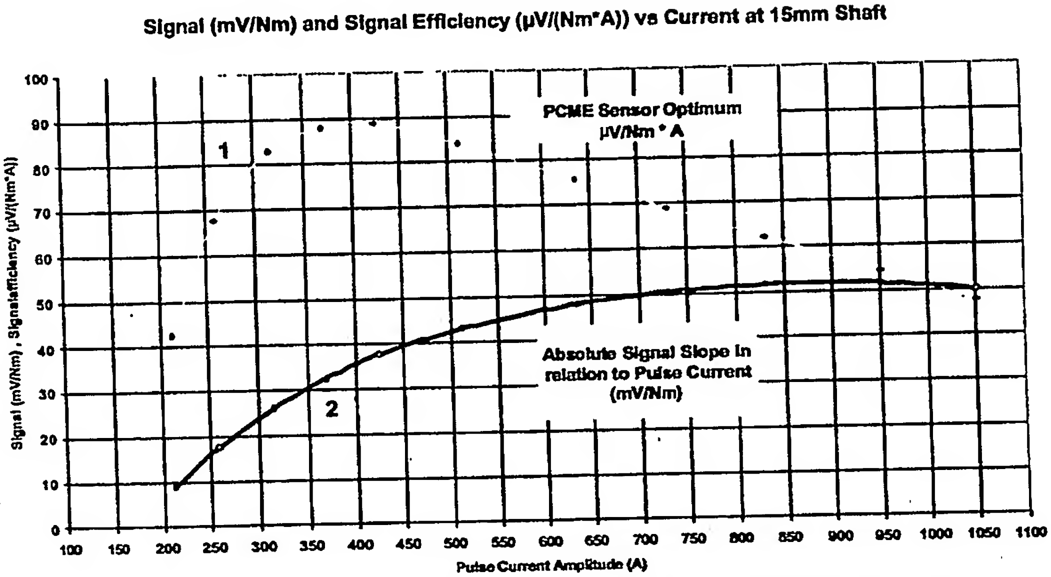
The Sensor-Output-Signal slope can be improved when using several rectangle shaped current-encoding-pulses in successions. In comparisons to other encoding-pulse-shapes the fast falling current-pulse signal slope of the rectangle shaped current pulse will prevent that the Sensor-Output-Signal slope may ever reach an optimal performance level. Meaning that after only a few current pulses (2 to 10) have been applied to the SH (or Shaft) the Sensor-Output Signal-Slope will no longer rise.

Discharge Current Pulse Shape

The Discharge-Current-Pulse has no Constant-Current ON-Time and has no fast falling edge. Therefore the primary and most felt effect in the magnetic encoding of the SH is the fast raising edge of this current pulse type.

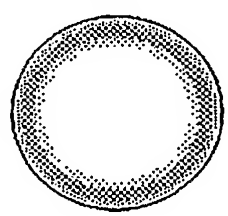


Graph: Sharp raising current edge and a typical discharging curve provides best results when creating a PCME sensor.



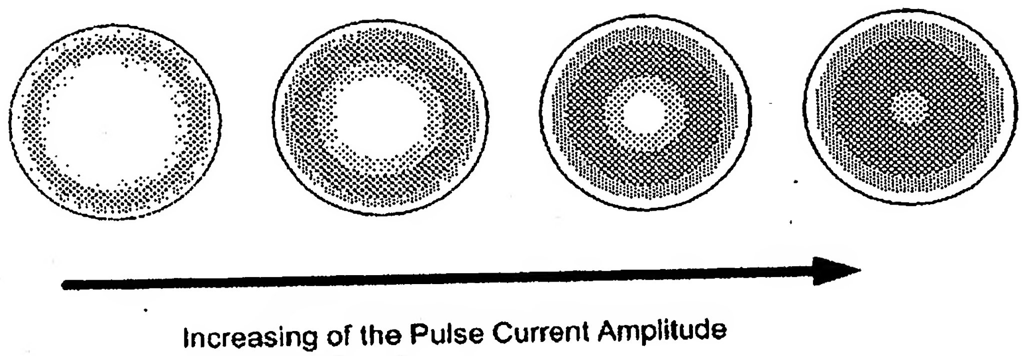
Graph: PCME Sensor-Output Signal-Slope optimization by identifying the right pulse current.

At the very low end of the pulse current scale (0 to 75 A for a 15 mm diameter shaft, 14CrNi14 shaft material) the "Discharge-Current-Pulse type is not powerful enough to cross the magnetic threshold needed to create a lasting magnetic field inside the Ferro magnetic shaft. When increasing the pulse current amplitude the double circular magnetic field structure begins to form below the shaft surface. As the pulse current amplitude increases so does the achievable torque sensor-output signal-amplitude of the secondary sensor system. At around 400A to 425A the optimal PCME sensor design has been achieved (the two counter flowing magnetic regions have reached their most optimal distance to each other and the correct flux density for best sensor performances.



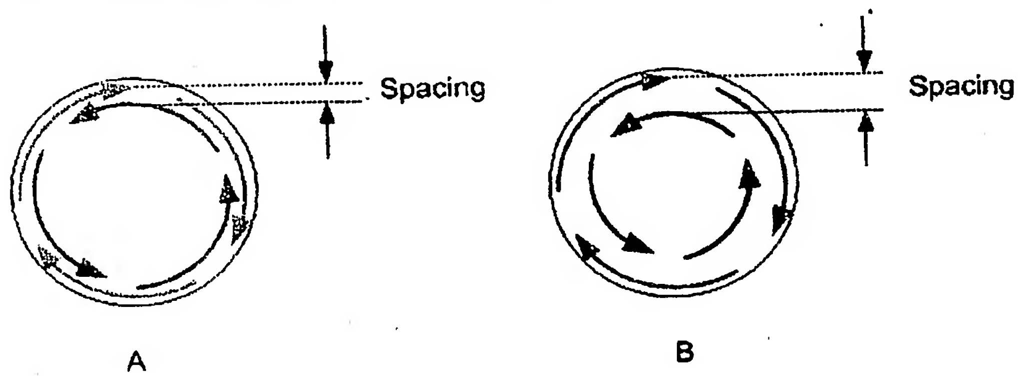
Drawing: Sensor Host (SH) cross section with the optimal PCME electrical current density and location during the encoding pulse.

When increasing further the pulse current amplitude the absolute, torque force related, sensor signal amplitude will further increase (curve 2) for some time while the overall PCME-typical sensor performances will decrease (curve 1). When passing 900A Pulse Current Amplitude (for a 15 mm diameter shaft) the absolute, torque force related, sensor signal amplitude will begin to drop as well (curve 2) while the PCME sensor performances are now very poor (curve 1).



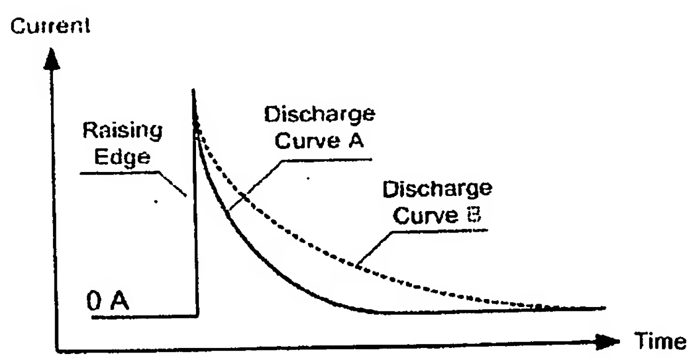
Drawing: Sensor Host (SH) cross sections and the electrical pulse current density at different and increasing pulse current levels.

As the electrical current occupies a larger cross section in the SH the spacing between the inner circular region and the outer (near the shaft surface) circular region becomes larger.



Drawing: Better PCME sensor performances will be achieved when the spacing between the Counter-Circular "Picky-Back" Field design is narrow (A).

The desired double, counter flow, circular magnetic field structure will be less able to create a close loop structure under torque forces which results in a decreasing secondary sensor signal amplitude.

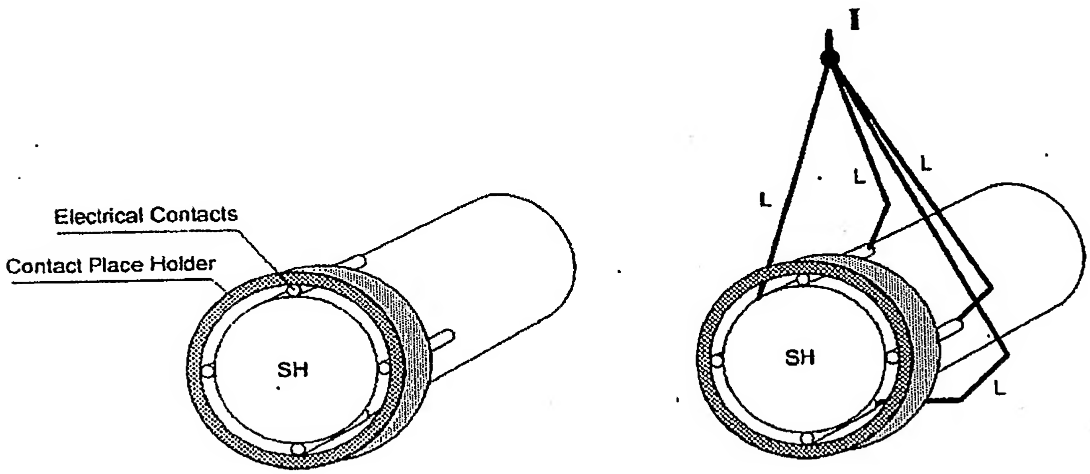


Graph: Flattening-out the current-discharge curve will also increase the Sensor-Output Signal-Slope.

When increasing the Current-Pulse discharge time (making the current pulse wider) (B) the Sensor-Output Signal-Slope will increase. However the required amount of current is very high to reduce the slope of the falling edge of the current pulse. It might be more practical to use a combination of a high current amplitude (with the optimal value) and the slowest possible discharge time to achieve the highest possible Sensor-Output Signal Slope.

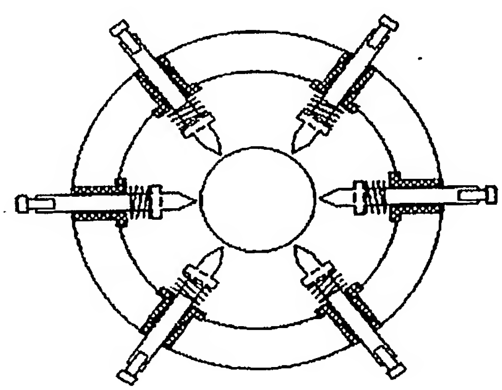
Primary Sensor Processing: Electrical Connection Devices

The PCME technology (it has to be noted that the term 'PCME' technology is used to refer to exemplary embodiments of the present invention) relies on passing through the shaft very high amounts of pulse-modulated electrical current at the location where the Primary Sensor should be produced. When the surface of the shaft is very clean and highly conductive a multi-point Cupper or Gold connection may be sufficient to achieve the desired sensor signal uniformity. Important is that the Impedance is identical of each connection point to the shaft surface. This can be best achieved when assuring the cable length (L) is identical before it joins the main current connection point (I)



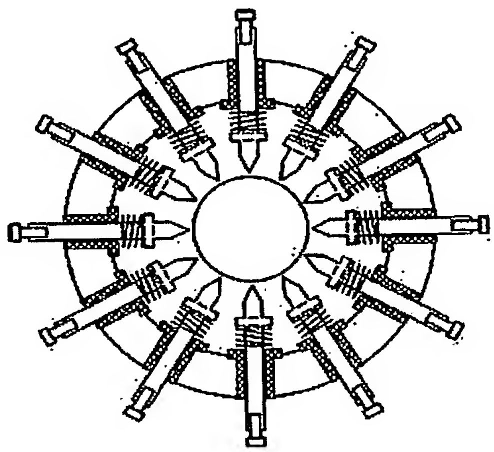
Drawing: Simple electrical multi-point connection to the shaft surface.

However, in most cases a reliable and repeatable multi-point electrical connection can be only achieved by ensuring that the impedance at each connection point is identical and constant. Using a spring pushed, sharpened connector will penetrate possible oxidation or isolation layers (maybe caused by finger prints) at the shaft surface.

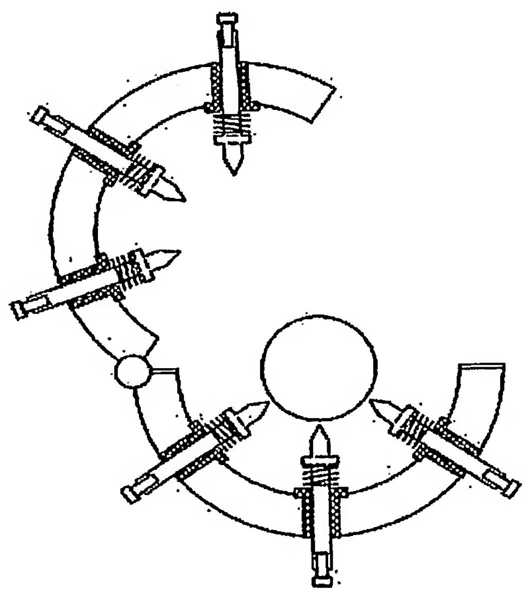


Drawing: Multi channel, electrical connecting fixture, with spring loaded contact points.

When processing the shaft it is most important that the electrical current is injected and extracted from the shaft in the most uniform way possible. The above drawing shows several electrical, from each other insulated, connectors that are held by a fixture around the shaft. This device is called a Shaft-Processing-Holding-Clamp (or SPHC). The number of electrical connectors required in a SPHC depends on the shafts outer diameter. The larger the outer diameter, the more connectors are required. The spacing between the electrical conductors has to be identical from one connecting point to the next connecting point. This method is called Symmetrical-"Spot"-Contacts.



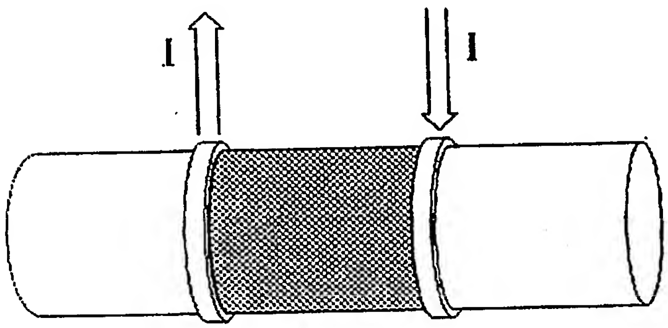
Drawing: Increasing the number of electrical connection points will assist the efforts of entering and exiting the Pulse-Modulated electrical current. It will also increase the complexity of the required electronic control system.



Drawing: Example of how to open the SPHC for easy shaft loading.

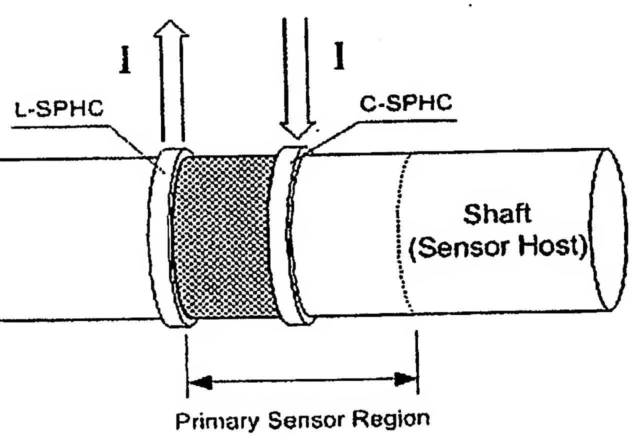
Primary Sensor Processing: Encoding

The encoding of the primary shaft can be done by using permanent magnets applied at a rotating shaft or using electric currents passing through the desired section of the shaft. When using permanent magnets a very complex, sequential procedure is necessary to put the two layers of closed loop magnetic fields, on top of each other, in the shaft. When using the PCME procedure the electric current has to enter the shaft and exit the shaft in the most symmetrical way possible to achieve the desired performances.



Drawing: Using two SPHCs (Shaft Processing Holding Clamps) that are placed at the borders of the planned sensing encoding region. Through one SPHC the pulsed electrical current (I) will enter the shaft, while at the second SPHC the pulsed electrical current (I) will exit the shaft. The region between the two SPHCs will then turn into the primary sensor.

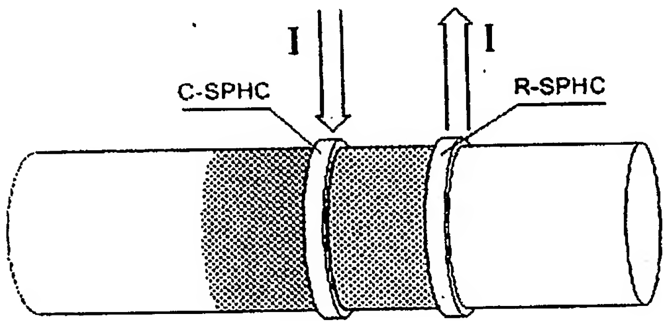
This particular sensor process will produce a Single Field (SF) encoded region. One benefit of this design (in comparison to those that are described below) is that this design is insensitive to any axial shaft movements in relation to the location of the secondary sensor devices. The disadvantage of this design is that when using axial (or in-line) placed MFS coils the system will be sensitive to magnetic stray fields (like the earth magnetic field).



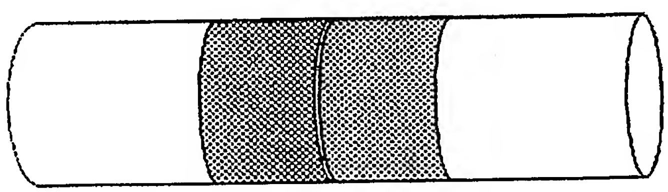
Drawing: A Dual Field (DF) encoded region (meaning two independent functioning sensor regions with opposite polarity, side-by-side) allows canceling the effects of uniform magnetic stray fields when using axial (or in-line) placed MFS coils. However, this

primary sensor design also shortens the tolerable range of shaft movement in axial direction (in relation to the location of the MFS coils). There are two ways to produce a Dual Field (DF) encoded region with the PCME technology. The sequential process, where the magnetic encoded sections are produced one after each other, and the parallel process, where both magnetic encoded sections are produced at the same time.

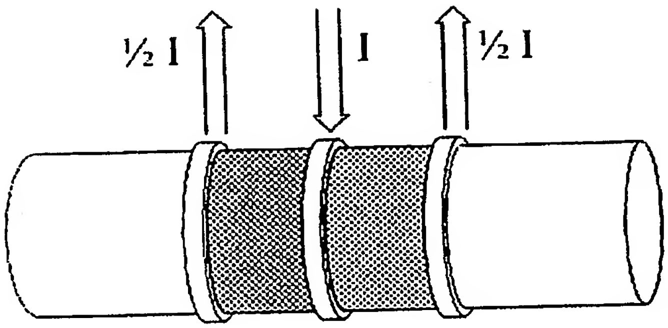
The first process step of the sequential dual field design is to magnetically encode one sensor section (identically to the Single Field procedure), whereby the spacing between the two SPHC has to be halve of the desired final length of the Primary Sensor region. To simplify the explanations of this process we call the SPHC that is placed in the center of the final Primary Sensor Region the Center SPHC (C-SPHC), and the SPHC that is located at the left side of the Center SPHC: L-SPHC.



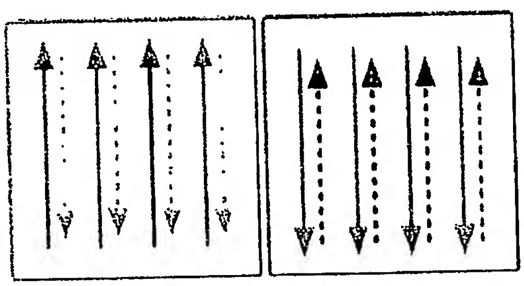
Drawing: The second process step of the sequential Dual Field encoding will use the SPHC that is located in the center of the Primary Sensor region (called C-SPHC) and a second SPHC that is placed at the other side (the right side) of the center SPHC, called R-SPHC. Important is that the current flow direction in the center SPHC (C-SPHC) is identical at both process steps.



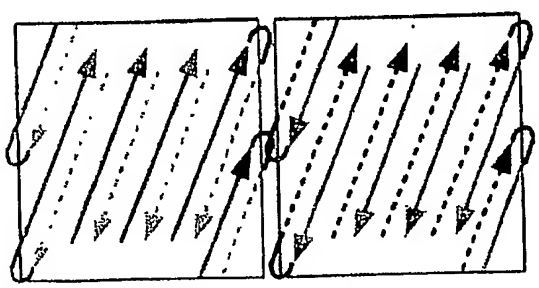
Drawing: The performance of the final Primary Sensor Region depends on how close the two encoded regions can be placed in relation to each other. And this is dependent on the design of the used center SPHC. The narrower the in-line space contact dimensions are of the C-SPHC, the better are the performances of the Dual Field PCME sensor.



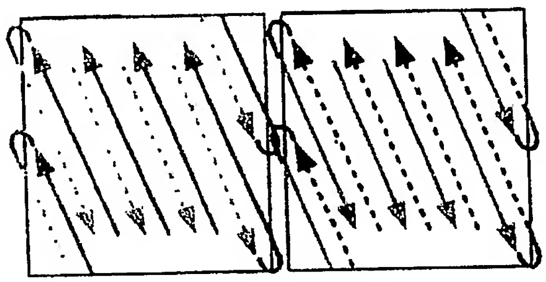
The above drawing shows the pulse application according to another exemplary embodiment of the present invention. As my be taken from the above drawing, the pulse is applied to three locations of the shaft. Due to the current distribution to both sides of the middle electrode where the current I is entered into the shaft, the current leaving the shaft at the lateral electrodes is only half the current entered at the middle electrode, namely ½ I. The electrodes are depicted as rings which dimensions are adapted to the dimensions of the outer surface of the shaft. However, it has to be noted that other electrodes may be used, such as the electrodes comprising a plurality of pin electrodes described later in this text.



Drawing: Magnetic flux directions of the two sensor sections of a Dual Field PCME sensor design when no torque is applied to the shaft. The counter flow magnetic flux loops do not interact with each other.



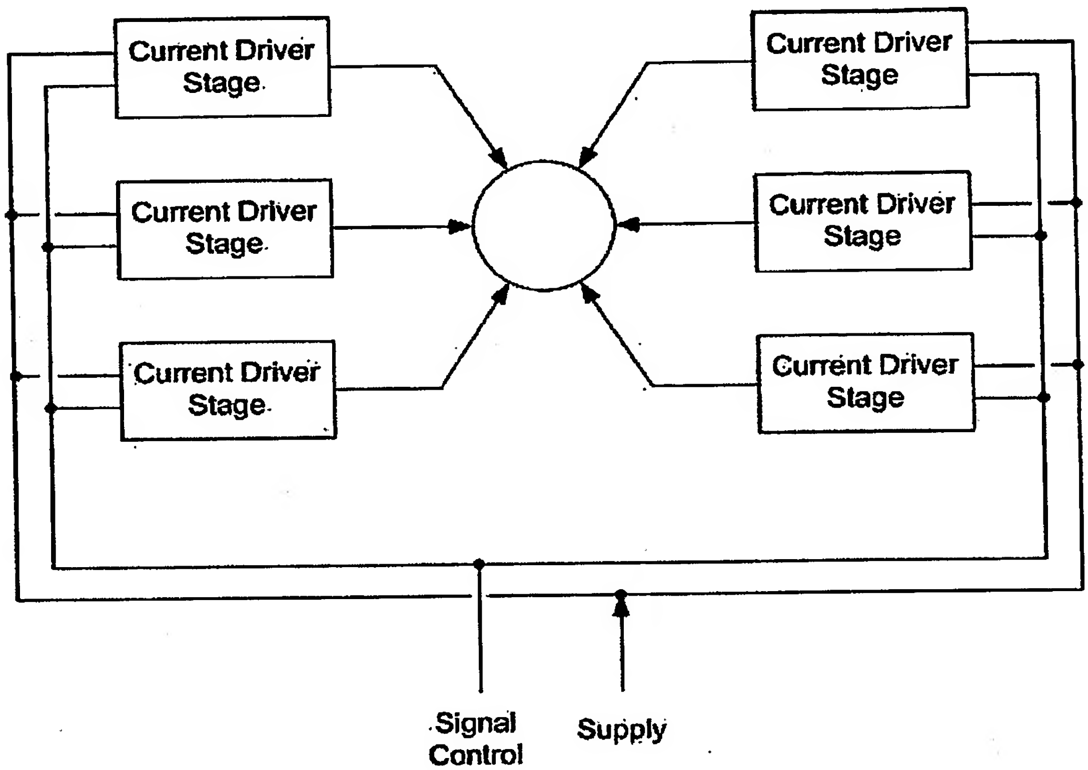
Drawing: When torque forces are applied in a particular direction then the magnetic flux loops begin to run with an increasing tilting angle inside the shaft. When the tilted magnetic flux reaches the PCME segment boundary then the flux line interacts with the counterflowing magnetic flux lines as shown above.



Drawing: When the applied torque direction is changing (for example from clock-wise to counter-clock-wise) so will change the tilting angle of the counterflow magnetic flux structures inside the PCM Encoded shaft.

Multi Channel Current Driver for Shaft Processing

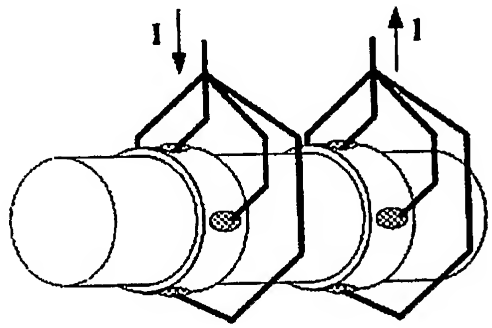
In cases where an absolute identical impedance of the current path to the shaft surface can not be guaranteed, then electric current controlled driver stages can be used to overcome this problem.



Drawing: A six-channel synchronized Pulse current driver system for small diameter Sensor Hosts (SH). As the shaft diameter increases so will the number of current driver channels.

From Bras Ring Contacts to Symmetrical "Spot" Contacts

When the shaft diameter is relative small and the shaft surface is clean and free from any oxidations at the desired Sensing Region, then a simple "Bras"-ring (or Copper-ring) contact method can be chosen to process the Primary Sensor.

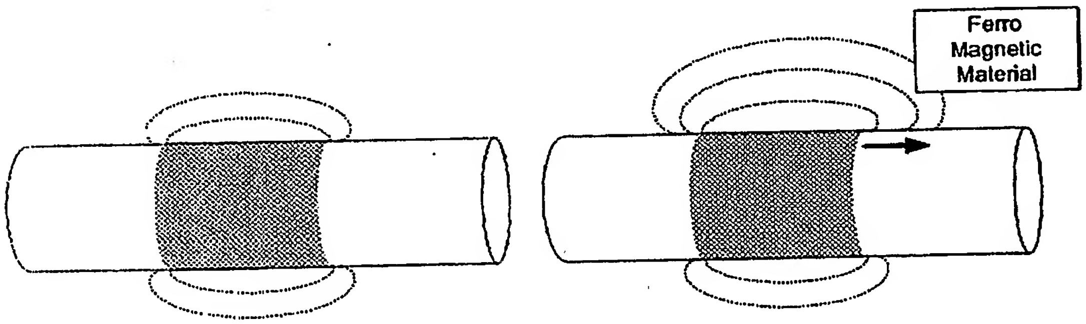


Drawing: Bras-rings (or Copper-rings) tightly fitted to the shaft surface, with solder connections for the electrical wires. The area between the two Bras-rings (Copper-rings) is the encoded region.

However, it is very likely that the achievable RSU performances are much lower then when using the Symmetrical "Spot" Contact method.

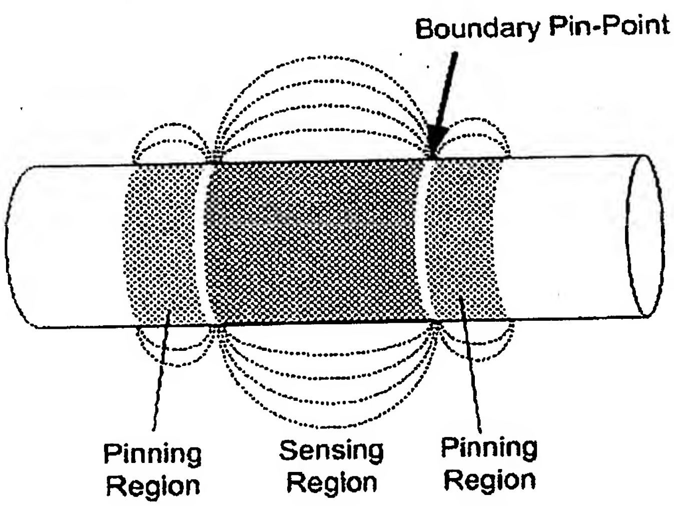
Hot-Spotting

A standard single field (SF) PCME sensor has very poor Hot-Spotting performances. The external magnetic flux profile of the SF PCME sensor segment (when torque is applied) is very sensitive to possible changes (in relation to Ferro magnetic material) in the nearby environment. As the magnetic boundaries of the SF encoded sensor segment are not well defined (not "Pinned Down") they can "extend" towards the direction where Ferro magnet material is placed near the PCME sensing region.



Drawing: A PCME process magnetized sensing region is very sensitive to Ferro magnetic materials that may come close to the boundaries of the sensing regions.

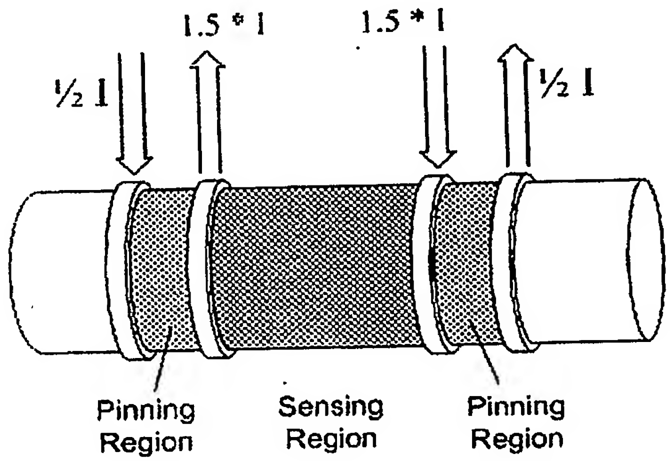
To reduce the Hot-Spotting sensor sensitivity the PCME sensor segment boundaries have to be better defined by pinning them down (they can no longer move).



Drawing: PCME processed Sensing region with two "Pinning Field Regions", one on each side of the Sensing Region.

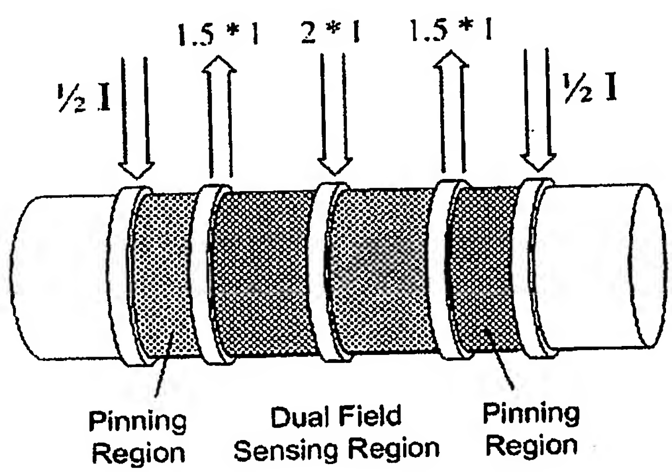
By placing Pinning Regions closely on either side the Sensing Region, the Sensing Region Boundary has been pinned down to a very specific location. When Ferro magnetic material is coming close to the Sensing Region, it may have an effect on the outer boundaries of the Pinning Regions, but it will have very limited effects on the Sensing Region Boundaries.

There are a number of different ways, according to exemplary embodiments of the present invention how the SH (Sensor Host) can be processed to get a Single Field (SF) Sensing Region and two Pinning Regions, one on each side of the Sensing Region. Either each region is processed after each other (Sequential Processing) or two or three regions are processed simultaneously (Parallel Processing). The Parallel Processing provides a more uniform sensor (reduced parasitic fields) but requires much higher levels of electrical current to get to the targeted sensor signal slope.



Drawing: Parallel Processing example for a Single Field (SF) PCME sensor with Pinning Regions on either side of the main sensing region, in order to reduce (or even eliminate) Hot-Spotting.

A Dual Field PCME Sensor is less sensitive to the effects of Hot-Spotting as the sensor center region is already Pinned-Down. However, the remaining Hot-Spotting sensitivity can be further reduced by placing Pinning Regions on either side of the Dual-Field Sensor Region.

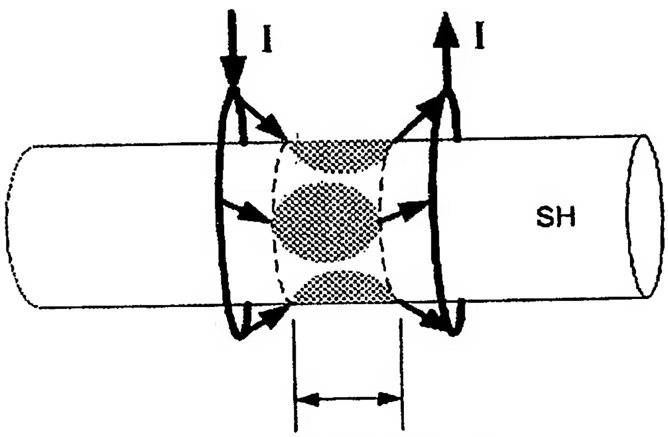


Drawing: Dual Field (DF) PCME sensor with Pinning Regions either side.

When Pinning Regions are not allowed or possible (example: limited axial spacing available) then the Sensing Region has to be magnetically shielded from the influences of external Ferro Magnetic Materials.

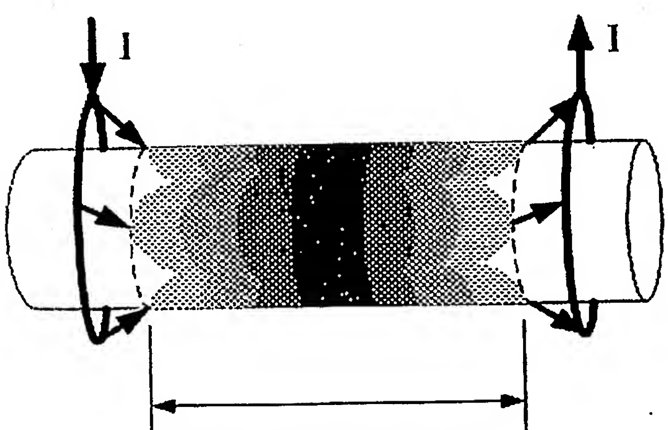
RSU

The RSU sensor performance are, according to current understanding, mainly depending on how circumferentially uniform the electrical current entered and exited the SH surface, and the physical space between the electrical current entry and exit points. The larger the spacing between the current entry and exit points, the better is the RSU performance.



PCM Encoding Segment

Drawing: When the spacings between the individual circumferential placed current entry points are relatively large in relation to the shaft diameter (and equally large are the spacings between the circumferentially placed current exit points) then this will result in very poor RSU performances. In such a case the length of the PCM Encoding Segment has to be as large as possible as otherwise the created magnetic field will be circumferentially non-uniform.



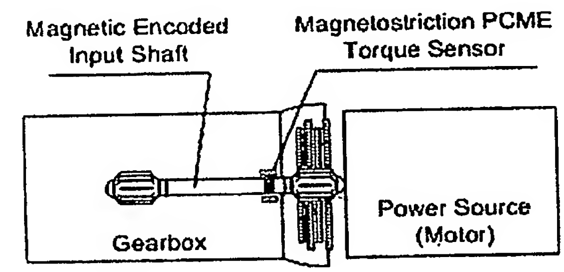
PCM Encoding Segment

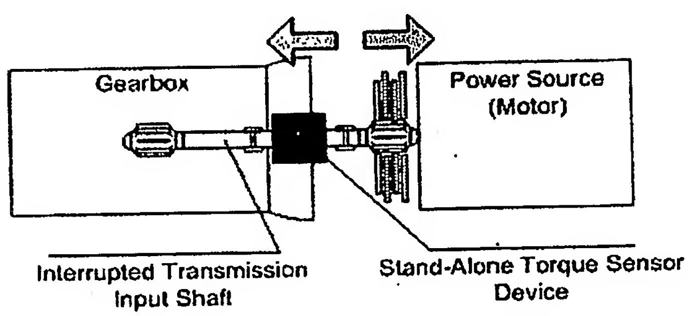
Drawing: By widening the PCM Encoding Segment the circumferentially magnetic field distribution will become more uniform (and eventually almost perfect) at the halve distance between the current entry and current exit points. Therefore the RSU performance of the PCME sensor is best at the halve way-point between of the current-entry / current-exit points.

Description of the basic design issues of a NCT sensor system

Without going into the specific details of the PCM-Encoding technology, the end-user of this sensing technology need to now some design details that will allow him to apply and to use this sensing concept in his application. The following pages describe the basic elements of a magnetostriction based NCT sensor (like the primary sensor, secondary sensor, and the SCSP electronics), what the individual components look like, and what choices need to be made when integrating this technology into an already existing product.

In principle the PCME sensing technology can be used to produce a stand-alone sensor product. However, in already existing industrial applications there is little to none space available for a "stand-alone" product. The PCME technology can be applied in an existing product without the need of redesigning the final product.

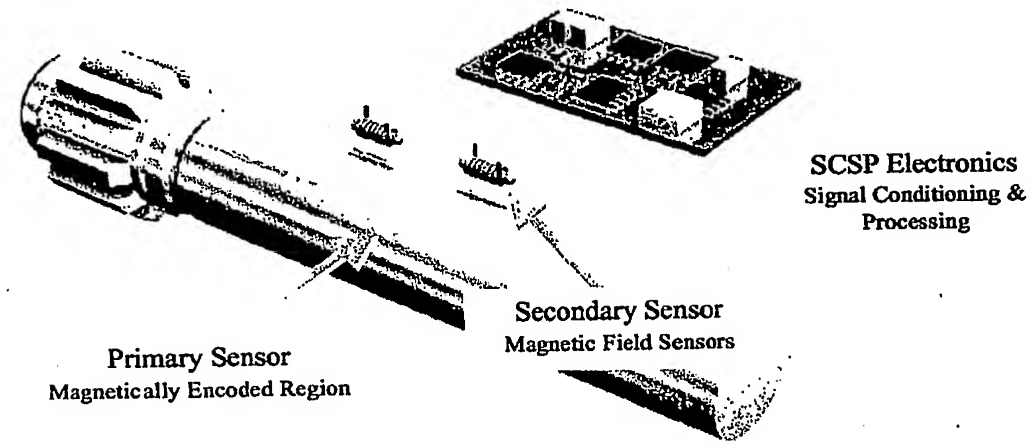




In case a stand-alone torque sensor device will be applied to a motor – transmission system it may require that the entire system need to undergo a major design change.

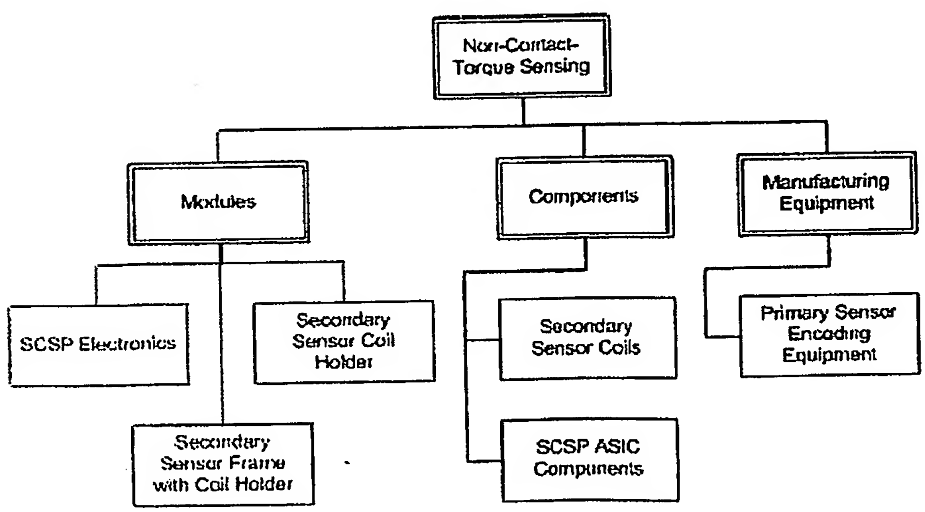
Sensor Components

The non-contact magnetostriction torque-sensor (NCT-Sensor) consists, according to an exemplary embodiment of the present invention, of three main functional elements: The ***Primary Sensor***, the ***Secondary Sensor***, and the ***Signal Conditioning & Signal Processing*** (SCSP) electronics.



Depending on the application type (volume and quality demands, targeted manufacturing cost, manufacturing process flow) the customer can chose to purchase either the ***individual components*** to build the sensor system under his own management, or can subcontract the production of the ***individual modules***.

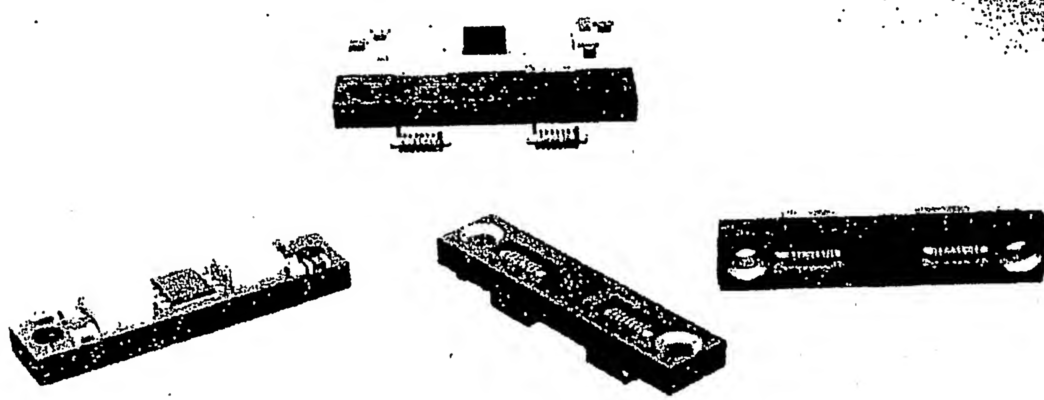
In cases where the annual production target is in the thousands of units it may be more efficient to integrate the "primary-sensor magnetic-encoding-process" into the customers manufacturing process. In such a case the customer needs to purchase application specific "magnetic encoding equipment".



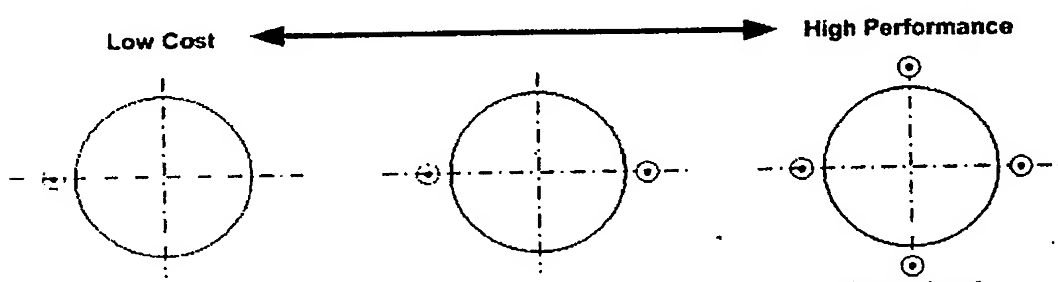
In high volume applications, where cost and the integrity of the manufacturing process are critical, it is typical that NCTE supplies only the individual basic components and equipment necessary to build a non-contact-torque sensor:

- ☐ ICs (surface mount packaged, Application-Specific Electronic Circuits)
- ☐ MFS-Coils (as part of the Secondary Sensor)
- ☐ Sensor Host Encoding Equipment (to apply the magnetic encoding on the shaft = Primary Sensor)

Depending on the required volume, the MFS-Coils can be supplied already assembled on a frame, and if desired, electrically attached to a wire harness with connector. Equally the SCSP (Signal Conditioning & Signal Processing) electronics can be supplied fully functional in PCB format, with or without the MFS-Coils embedded in the PCB.



The number of required MFS-coils is dependent on the expected sensor performance and the mechanical tolerances of the physical sensor design. In a well designed sensor system with perfect Sensor Host (SH or magnetically encoded shaft) and minimal interferences from unwanted magnetic stray fields, only 2 MFS-coils are needed. However, if the SH is moving radial or axial in relation to the secondary sensor position by more than a few tenths of a millimeter, then the number of MFS-coils need to be increased to achieve the desired sensor performance.



Cross Section of Primary Sensor (Shaft) and one pair of MFS-coils

Two pairs of MFS-coils

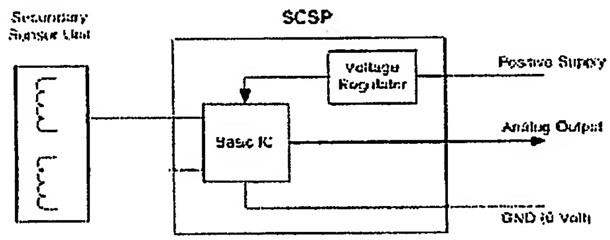
Four pairs of MFS-coils

Control and/or evaluation circuitry

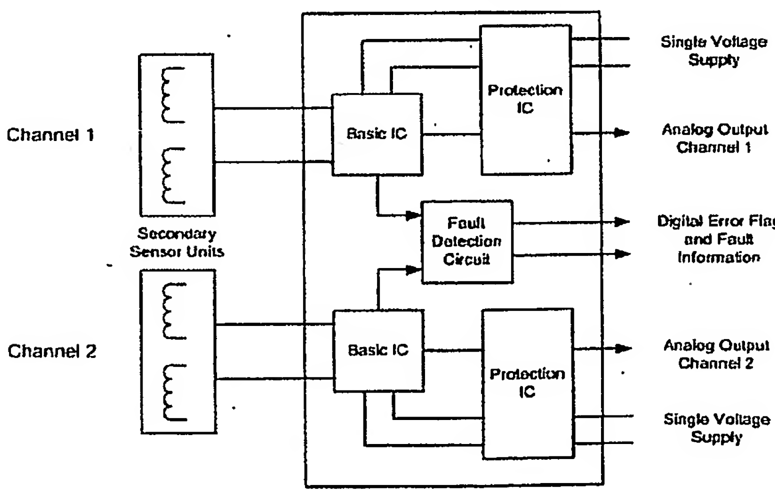
The SCSP electronics, according to an exemplary embodiment of the present invention, consist of the NCTE specific ICs, a number of external passive and active electronic circuits, the printed circuit board (PCB), and the SCSP housing or casing. Depending on the environment where the SCSP unit will be used the casing has to be sealed appropriately.

Depending on the application specific requirements NCTE (according to an exemplary embodiment of the present inevention) offers a number of different application specific circuits:

- ☐ Basic Circuit
- ☐ Basic Circuit with integrated Voltage Regulator
- ☐ High Signal Bandwidth Circuit
- ☐ Optional High Voltage and Short Circuit Protection Device
- ☐ Optional Fault Detection Circuit



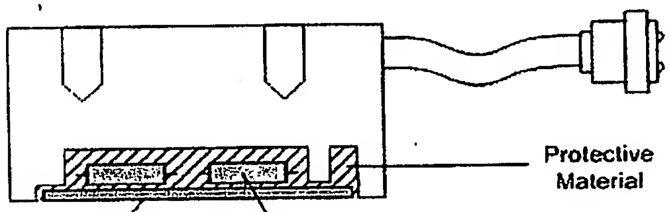
Example 1: Single channel, low cost sensor electronics solution



Example 2: Dual channel, short circuit protected system design with integrated fault detection. This design consists of 5 ASIC devices and provides a high degree of system safety. The Fault-Detection IC identifies when there is a wire breakage anywhere in the sensor system, a fault with the MFS coils, or a fault in the electronic driver stages of the "Basic IC".

Secondary Sensor Unit

The Secondary Sensor consists of the elements: One to eight **MFS** (Magnetic Field Sensor) Coils, the **Alignment- & Connection-Plate**, the wire harness with connector, and the **Secondary-Sensor-Housing**.



The MFS-coils are mounted onto the alignment-Plate. Usually the Alignment-Plate allows that the two connection wires of each MFS-Coil are soldered / connected in the appropriate way. The wire harness is connected to the alignment plate. This, completely assembled with the MFS-Coils and wire harness, is then embedded or held by the Secondary-Sensor-Housing.

The main element of the MFS-Coil is the core wire, which has to be made out of an amorphous-like material.

Depending on the environment where the Secondary-Sensor-Unit will be used, the assembled Alignment Plate has to be covered by protective material. This material can not cause mechanical stress or pressure on the MFS-coils when the ambient temperature is changing.

In applications where the operating temperature will not exceed +110 deg C the customer has the option to place the SCSP electronics (ASIC) inside the secondary sensor unit (SSU). While the ASIC devices can operated at temperatures above +125 deg C it will become increasingly more difficult to compensate the temperature related signal-offset and signal-gain changes.

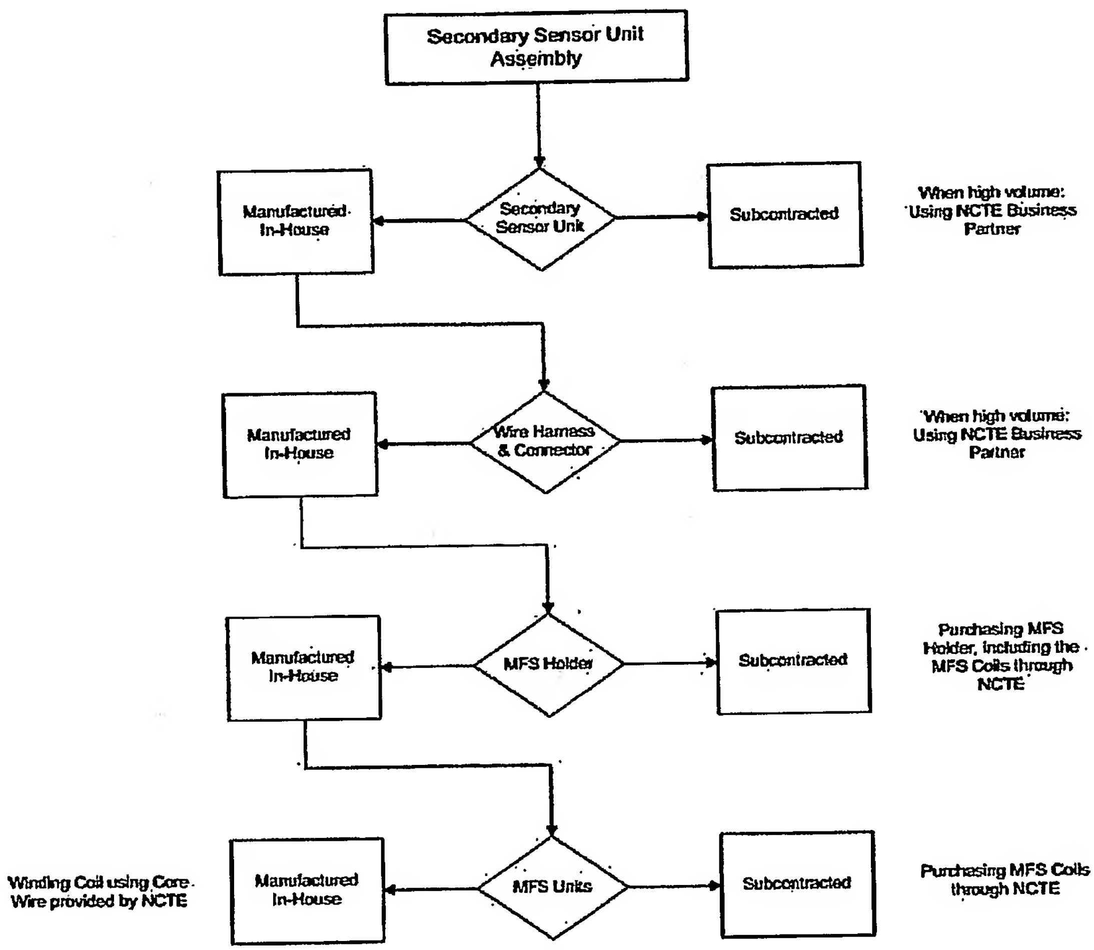
The recommended maximal cable length between the MFS-coils and the SCSP electronics is 2 meters. When using the appropriate connecting cable, distances of up to 10 meters are achievable. To avoid signal-cross-talk in multi-channel applications (two independent SSU's operating at the same Primary Sensor location = Redundant Sensor Function), specially shielded cable between the SSU's and the SCSP Electronics should be considered.

When planning to produce the Secondary-Sensor-Unit (SSU) the producer has to decide which part / parts of the SSU have to be purchased through subcontracting and which manufacturing steps will be made in-house.

Secondary Sensor Unit Manufacturing Options

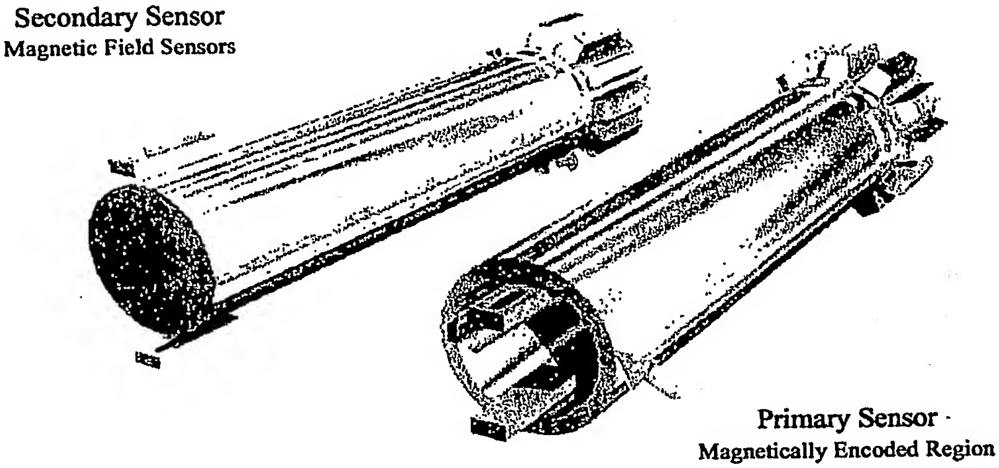
When integrating the NCT-Sensor into a customized tool or standard transmission system then the systems manufacturer has several options to choose from:

- ☐ custom made SSU (including the wire harness and connector)
- ☐ selected modules or components; the final SSU assembly and system test may be done under the customer's management.
- ☐ only the essential components (MFS-coils or MFS-core-wire, Application specific ICs) and will produce the SSU in-house.

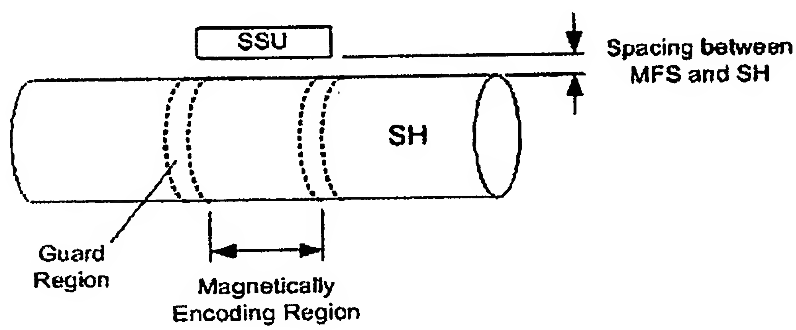


Primary Sensor Design

The SSU (Secondary Sensor Units) can be placed outside the magnetically encoded SH (Sensor Host) or, in case the SH is hollow, inside the SH. The achievable sensor signal amplitude is of equal strength but has a much better signal-to-noise performance when placed inside the hollow shaft.



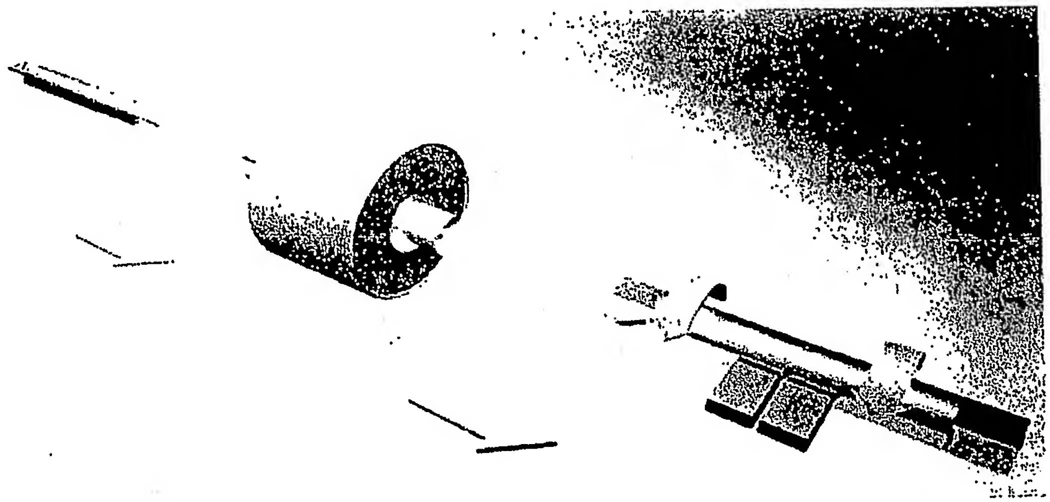
Improved sensor performances may be achieved when the magnetic encoding process is applied to a straight and parallel section of the SH (shaft). For a shaft with 15 mm to 25 mm diameter the optimal minimum length of the Magnetically Encoded Region is 25 mm. The sensor performances will further improve if the region can be made as long as 45 mm (adding Guard Regions). In complex and highly integrated transmission (gearbox) systems it will be difficult to find such space. Under more ideal circumstances the Magnetically Encoding Region can be as short as 14 mm, but this bears the risk that not all of the desired sensor performances can be achieved.



The spacing between the SSU (Secondary Sensor Unit) and the Sensor Host surface, according to an exemplary embodiment of the present invention, should be held as small as possible to achieve the best possible signal quality.

Primary Sensor Encoding Equipment

Depending on which magnetostriction sensing technology will be chosen, the Sensor Host (SH) needs to be processed and treated accordingly. The technologies vary by a great deal from each other (ABB, FAST, FT, Kubota, MDI, NCTE, RM, Siemens, …) and so does the processing equipment required. Some of the available magnetostriction sensing technologies don't need any physical changes to be made on the SH and rely only on magnetic processing (MDI, FAST, NCTE).



While the MDI technology is a two phase process, the FAST technology is a three phase process, and the NCTE technology a one phase process, called PCM Encoding.

Note: Be aware that after the magnetic processing the Sensor Host (SH or Shaft) has become a "precision measurement" device and has to be treated accordingly. The magnetic processing should be the very last step before the treated SH is carefully placed in its final location.

The magnetic processing should be an integral part of the customer's production process (in-house magnetic processing) under the following circumstances:

- ☐ High production quantities (like in the thousands)
- ☐ Heavy or difficult to handle SH (e.g. high shipping costs)
- ☐ Very specific quality and inspection demands (e.g. defense applications)

In all other cases it may be more cost effective to get the SH magnetically treated by a qualified and authorized subcontractor, such as NCTE. For the "in-house" magnetic processing dedicated manufacturing equipment is required. Such equipment can be operated fully manually, semi-automated, and fully automated. Depending on the complexity and automation level the equipment can cost anywhere from EUR 20k to above EUR 500k.

In this application, there are a number of "new" acronyms used as otherwise some explanations and descriptions may be difficult to read. While the acronyms "ASIC", "IC", and "PCB" are already market standard definitions, there are many new terms that have been created in relation to the magnetostriction based NCT sensing technology. It should be noted that in this application, when there is a reference to NCT technology, it is referred to exemplary embodiments of the present invention.

Acronym	Description	Category
ASIC	Application Specific IC	Electronics
DF	Dual Field	Primary Sensor
EMF	Earth Magnetic Field	Test Criteria
FS	Full Scale	Test Criteria
Hot-Spotting	Sensitivity to nearby Ferro magnetic material	Specification
IC	Integrated Circuit	Electronics
MFS	Magnetic Field Sensor	Sensor Component
NCT	Non Contact Torque	Technology
PCB	Printed Circuit Board	Electronics
PCME	Pulse Current Modulated Encoding	Technology
POC	Proof-of-Concept	
RSU	Rotational Signal Uniformity	Specification
SCSP	Signal Conditioning & Signal Processing	Electronics
SF	Single Field	Primary Sensor
SH	Sensor Host	Primary Sensor
SPHC	Shaft Processing Holding Clamp	Processing Tool
SSU	Secondary Sensor Unit	Sensor Component

According to an exemplary embodiment of the present invention, there is provided a torque sensor, comprising:

a first sensor element with a magnetically encoded region; and

a second sensor element with at least one magnetic field detector;

wherein the first sensor element has a surface;

wherein, in a direction essentially perpendicular to the surface of the first sensor element, the magnetically encoded region of the first sensor element has a magnetic field structure such that there is a first magnetic flow in a first direction and a second magnetic flow in a second direction;

wherein the first direction is opposite to the second direction;

wherein the first sensor element is a shaft;

wherein in a cross-sectional view of the shaft, there is a first circular magnetic flow having the first direction and a first radius and a second circular magnetic flow having the second direction and a second radius; and

wherein the first radius is larger than the second radius.

Abstract

The present invention relates to a torque sensor, comprising a first sensor element with a magnetically encoded region and a second sensor element with at least one magnetic field detector. The first sensor element has a surface. In a direction essentially perpendicular to the surface of the first sensor element, the magnetically encoded region of the first sensor element has a magnetic field structure such that there is a first magnetic flow in a first direction and a second magnetic flow in a second direction, wherein the first direction is opposite to the second direction.